TITLE OF THE INVENTION

OPTICAL TRANSMISSION SYSTEM AND METHOD

BACKGROUND OF THE INVENTION

The invention relates to optical transmission systems and methods, more
5   especially but not exclusively to systems and methods based on encoding of optical
signals using spread spectrum techniques.

All optical generation and recognition of a packet address is a key
requirement for future high capacity optical networks. Recently optical code division
multiple access (OCDMA) technology was adopted for header recognition in optically
10   routing data packets, and proved to be a reliable approach [1]. An important issue
related to the OCDMA approach is how reliably the optical signals of the code
sequences can be generated and recognized at the transceiver ends.

A number of approaches for generating optical code signals have been
reported to date, these include; arrays of optical fiber delay lines [2], planar lightwave
15   circuits (PLCs) [3], arrayed waveguide gratings (AWGs) [4], and fiber grating based
devices (FBGs) [5,6].

Recently, the use of superstructure fiber Bragg gratings (SSFBGs) has been
demonstrated as an alternative approach for encoding/decoding [6].

However, the use of OCDMA is associated with complexity at the transmitter,
20   especially for multi-user systems with large numbers of users, where a separate
encoder grating needs to be added for each user.

SUMMARY OF THE INVENTION

According to a first aspect of the invention there is provided an optical transmission system comprising:

5   (a)   an optical transmitter including an input for receiving an encoding signal and an encoder arranged to encode an optical signal with any one of a plurality of encoding signatures according to the encoding signal;

      (b)   a transmission link for conveying the encoded optical signal from the optical transmitter; and

10   (c)   an optical receiver comprising a grating decoder connected to receive the encoded optical signal from the input, the grating decoder incorporating a decoding signature complementary to a matched one of the encoding signatures so as to decode the encoded optical signal when encoded with the matched one of the encoding signatures.

15   Thus, instead of the prior art approach of using identical technologies for implementing both the encoder and decoder, we propose a hybrid system that uses (passive) grating decoders at the receiver in combination with drive-signal-based encoders at the transmitter. In this way, reconfigurability can be retained for the transmitter hardware, whereas the advantages of grating decoders can be exploited at 20 the receivers.

By matched, it is meant that the impulse response of the decoder in the time domain bears a strong correlation in terms of both its amplitude and phase to a temporally inverted version of the encoded signal that we wish to decode. The resulting decoded signal in the time domain resembles closely the autocorrelation 25 function of the encoded signal. By appropriate choice of code it is possible to arrange for the decoded signal to have a readily distinguishable feature, most commonly a short distinct spike, that can be used as a code recognition signature.

In an embodiment, we demonstrate how SSFBGs can be used as grating decoders to recognize code sequences generated from an optical fiber delay line based 30 encoder.

The proposed hybrid approach is applicable to unipolar gratings, as shown in the specific examples, and also to multipolar gratings, such as bipolar or quadrupolar gratings.

The transmitter may incorporate a variety of signal modulation approaches. Ammplitude or phase modulators may be used, or a combination of both. In one embodiment, the transmitter includes a modulator having drive electrodes and the encoding signal is an electrical signal connected to the drive electrodes. The modulator may comprise an electro-acoustic modulator or an electro-optic modulator, for example. In another embodiment, the transmitter includes an optical delay line encoder. In a further embodiment, the transmitter includes an electrically driven laser source and the encoding signal is an electrical signal connected as a drive current to bias the laser source.

The grating decoder may additionally incorporate a filtering function to compensate for distortions that result from the application of the encoding signal to the optical signal, typically as a result of electrical-to-optical conversion distortion characteristics. By 'distortions' we include all effects that distort either, or both, the amplitude and phase of the optical signal relative to the encoding signal, and which includes both nonlinear amplitude responses and chirping effects, for example.

In a preferred embodiment, the grating decoder comprises a refractive index modulation induced grating. The refractive index modulation induced grating may be formed in an optical fiber or other waveguide.

The grating decoder may be configured to decode a spread-spectrum encoded optical signal, e.g. an OCDMA encoded optical signal.

According to a second aspect of the invention there is provided an optical transmission method comprising:

(a)   encoding an optical signal with any one of a plurality of encoding signatures according to an encoding signal;

(b)   transmitting the encoded optical signal over a transmission link; and

(c)   decoding the encoded optical signal using a grating decoder incorporating a decoding signature complementary to a matched one of the encoding signatures.

According to a third aspect of the invention there is provided an optical transmitter comprising:

an optical source for generating an optical signal modulated with a content-bearing signal and having a predictable distortion characteristic induced during modulation of the optical signal; and

a grating decoder incorporating a filtering function configured to compensate for the distortion characteristic and arranged to process the optical signal to compensate for the distortion characteristic.

With the invention it is possible to correlate (provide matched filtering) directly with the output from a modulated optical source. For example the source can be a directly modulated gain-switch diode, and externally modulated DFB laser, or a mode-locked fiber ring laser with external modulation.

The system and method can also include one or more of the following features:

1. Incorporation of both dispersion-compensating and decoding gratings into a single superstructure grating.

2. Addition of multiple codes within a single grating – for example two codes at different central wavelengths.

3. Further extension of either the grating length or reduction in chip size to increase the code length to codes of greater than 5000 chips, or more, allowing rapid increases in simultaneous users.

4. More complex superstructure profiles including amplitude and phase features to shape controllably the individual chip shapes.

5. Incorporation of simultaneous additional, multiple functionality with a single grating (decoding or coding) structures e.g. loss compensation and dispersion compensation (2nd and 3rd order).

6. The apparatus may be reconfigured such that the superstructure grating as above is used in transmission mode rather than reflective mode.

7. To use higher reflectivity versions of the decoder gratings designed using more advanced design algorithms (e.g. inverse scattering techniques) other than by the Fourier approach.

8. To use cascades of one or more decode gratings.

9. Use advanced codes such as those developed by the mobile-communications community for optimized correlation function definition e.g. M-sequences, Gold sequences or Kasami codes.

10. Use a combination of a decoder grating and nonlinear element such as a semiconductor optical amplifier or fiber-based nonlinear switch to enhance the correlation contrast and effect further enhanced processing functions such as optical routing, header removal and rewrite, data packet loading.

11. Use parallel arrays of coder-decoder gratings to enhance multi-user operation.

12. Use of coder/decoder approach to allow reduction of nonlinear optical effects by extending the bit duration in the time domain, thereby reducing optical intensities.

13. Use superstructure gratings to shape optical pulses (that may be of non-optimal form) for a given transmission technique or optical processing function to a more-desirable functional form for onward transmission or processing, e.g. chirped pulse to transform limited pulse conversion, soliton to super-Gaussian pulses, soliton to dispersion solitons, Gaussian pulses to square pulses.

14. Extend the grating bandwidths of decode grating to up to 200nm or further.

15. Extend technique to other wavelength regimes in the range 700nm to 2000nm or further.

16. Addition of wavelength division multiplexers and demultiplexers such as arrayed waveguide gratings to facilitate multi-wavelength operation, with one or more wavelengths being operated under the code-division multiplexing technique described previously.

17. Operation of the system with synchronous transmitters and receivers.

18. Operation of the system with asynchronous transmitters and receivers.

19. Operation of the system with a combination of synchronous and asynchronous transmitters and receivers.

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Aspects of this invention include code division multiplexing (CDM) system architectures, a CDM architecture for optical communications, or a combined CDM and WDM system architecture for optical communications. By CDM we mean not only code-division multiplexing but also include ultrafast packet-switched, or other

10 OTDM networks or transmissions systems.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the invention and to show how the same may be carried into effect reference is now made by way of example to the accompanying
5   drawings.

Fig. 1(a) Experimental setup in a first embodiment; where EFRL: erbium doped fiber ring laser, PC: polarization controller, PM isolator: polarization maintaining isolator, SSFBG: superstructure fiber Bragg grating.
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Fig. 1(b) reflectivity spectrum for an example 7-chip unipolar SSFBG for the first embodiment.

Fig. 2(a) Delay line encoder (first embodiment):
15   *Above:* Intensity SHG autocorrelation traces of the encoded sequence (solid line: experiment, dashed line: theory) at the output of the particular encoder.
Below: Theoretical and experimental traces of the encoded waveform at 10 Gbit/s with 25GHz bandwidth limitation included.

20   Fig. 2(b) SSFBG encoder (prior art):
Above: Intensity SHG autocorrelation traces of the encoded sequence (solid line: experiment, dashed line: theory) at the output of the particular encoder.
Below: Theoretical and experimental traces of the encoded waveform at 10 Gbit/s with 25GHz bandwidth limitation included.
25   The SSFBG encoder is being reflected from the opposite side and hence the time inversed nature of the encoded waveform.

Fig. 3. (a) A fiber delay line encoder - SSFBG decoder system (first embodiment).

Above: Intensity SHG autocorrelation traces of the decoded signal (solid line: experiment, dashed line: theory)

Below: Numerically calculated and measured experimental results of the oscilloscope traces of the decoded signal taking into account the 25GHz bandwidth limitation of

5   the detector at 10 Gbit/s.

Fig. 3(b) A SSFBG based encoder – SSFBG decoder system (prior art).

Intensity SHG autocorrelation traces of the decoded signal (solid line: experiment, dashed line: theory)

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Fig. 4 Experimental setup in a second embodiment.

Fig. 5 Experimental setup in a third embodiment.

DETAILED DESCRIPTION

Fig. 1(a) shows an experimental set up according to a first embodiment used to test the hybrid approach of the invention. The first embodiment provides a 10-Gbit/s all-optical code generation and recognition system based on a hybrid approach of optical fiber delay line and superstructure fiber Bragg grating technologies.

A 10GHz regeneratively mode locked erbium fiber ring laser (EFRL) producing 2ps pulses is used as the source. The operating wavelength of the laser is 1554nm corresponding to the center wavelength of the SSFBG. The pulses are launched into the optical fiber delay line encoder through a splitter to generate the desired code. As the decoder, a SSFBG also operating as a matched filter [7], is used to recognize the encoded sequence. The resulting pulse form after reflection from the decoder grating is measured and analyzed using both a fast photodiode/scope (~25GHz bandwidth) and an autocorrelator (<100fs resolution).

The optical fiber delay line encoder consists of four parallel fiber delay arms, where each delay is set according to a 7-chip M-sequence amplitude code (1110010). Each delay τ corresponds to 6.4ps, hence a chip rate of 160 Gchip/s, and the encoded sequence has a total duration of 44.8ps. The M-sequence code is chosen so that the autocorrelation features upon decoding will have a single dominant, well-defined peak with low level cross correlation features. A polarization controller (PC) in each delay line is used to align the individual pulses to a single polarization axis. The delayed pulses are then recombined and launched into a polarization maintaining (PM) isolator to confirm the same polarization state of the composite delayed pulses.

The 7-chip amplitude modulated SSFBG decoder was written using our continuous grating writing technique as reported in [8]. It has a total length of 4.62mm with an absolute reflectivity of ~4%. The individual chip duration is 6.4ps corresponding to a chip rate of 160 Gchip/s.

Fig. 1(b) shows the measured reflectivity profile of the SSFBG decoder (solid line) and shows good agreement with the theoretical calculation (dashed line).

In order to quantify the quality of the fiber delay line encoder, we performed a series of code generation experiments to examine the temporal characteristics of the pulse forms generated from the fiber delay line. These results then were compared to the pulse form generated by using a SSFBG as the decoding element.

5　　　Fig. 2(a) shows the temporal response of the fiber delay line encoder as measured using the SHG autocorrelator as well as the direct electronic measurements on the oscilloscope with ~25GHz spectral bandwidth. The measured autocorrelation and oscilloscope traces of encoded signals are found to be in good agreement with the theoretical predictions confirming not only the formation of the correct code patterns but also the desired individual chip separation of 6.4ps.

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Fig. 2(b) shows the equivalent results of the pulse forms on reflection from the SSFBG decoder (in this case used as the encoder) with evidence of good qualitative coincidence between experiment and theory.

To characterize the full hybrid system, the two different schemes of encoding/decoding (Delay line encoder:SSFBG decoder, SSFBG encoder:SSFBG decoder) then were put together and the results of the code recognition analysed and compared. In the case of the fiber delay line encoder, fine control of both the phase and polarization is required to obtain the optimum results. This is because each delayed pulse experiences a random phase change, which can lead to changes in the form of the output recognition pattern [2].

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Fig. 3(a) shows a direct comparison of the SHG autocorrelations of the code recognition signature of the 7-chip unipolar code against the theoretical predictions. Good agreement is found between them as shown. The well-defined code recognition peak was found to have a pulse width of ~12.4ps. Despite the limitation of oscilloscope bandwidth, we were able to obtain a single peak deconvolved decoded pulse form with good agreement to the theoretical calculations.

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Fig. 3(b) shows for comparison the equivalent SHG autocorrelation traces obtained in a non-hybrid system with SSFBG encoder and decoder.

In conclusion, we have demonstrated both experimentally and theoretically that SSFBGs can be used to recognize codes generated from another pattern

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generating scheme, in this case fiber delay lines. These results illustrate that the SSFBG approach is compatible with other technologies for code generation. Our experiment constitutes the first demonstration of a hybrid all-optical encoder-decoder system, an approach that could prove a necessary solution for reconfigurable point-to-

5   point optical correlation systems.

Fig. 4 shows an experimental setup according to a second embodiment. An optical source 10 in the form of a distributed feedback (DFB) laser diode (LD) is connected to an encoder unit 20. The encoder unit 20 has an electrical input 22 for receiving an encoding signal. This input is split by a control unit 23 into amplitude

10   and phase components. One output, conveying the amplitude component, is connected to an electro-absorption modulator (EAM) 24 to define the code length and/or associated amplitude modulation. A second output is connected to a phase modulator (PM) 26 via a variable delay line 28 which is used to encode associated phase information associated with the code. The above-described components

15   collectively form a transmitter (Tx) part of the system. The transmitter Tx is linked to a receiver part (Rx) of the system by a transmission line 30 which leads to an optical circulator 40 for directing the transmitted signal to a SSFBG 42 arranged in reflection with the circulator 40 to decode the signal by applying the reverse functional manipulation to that applied at the transmitter by the encoder unit 20. Finally, a

20   photodiode (PD) 44 is shown arranged at the receiver for converting the decoded optical signal into an electrical signal, as may sometimes be required.

Fig. 5 Experimental setup in a third embodiment. An optical source 50 in the form of a distributed feedback (DFB) laser diode (LD) is provided. The source 50 is driven with a drive current from an input 52. In this embodiment, the drive current is

25   used to directly modulate and encode the optical signal as it is generated. As is widely known in the art, that this kind of direct driving of a laser diode is prone to result in significant nonlinearities in the signal modulation as a result of the nonlinear nature of the gain spectrum of the laser diode, and its fast gain dynamics. Consequently, this approach is often avoided. However, in the present embodiment,

30   this approach is deliberately taken and the flexibility provided by a SSFBG is used to

-12-

cancel out, or at least compensate for, the non-linearities. Namely, a SSFBG is arranged to receive the output from the source 50 via a circulator 54. The SSFBG provides decoding as in the previous embodiments, but in addition incorporates a filtering function to compensate for nonlinearity/distortion that results from the

5   application of the drive signal to the laser diode.

This approach can be generalized so that the same structure as shown in the figure could be used, where the grating solely has the function of filtering out the non-linearities. In this case, the grating could be provided at the transmitter for correcting the signal generated by the directly driven laser.

10   Note also that since an OCDMA system is ordinarily a linear optical system it is also possible to envisage hybrid OCDMA systems such as those described herein in which an SSFBG system is used in the transmitter and an alternative decoding technology is used within the receiver. Thus according to a further aspect of the invention there is provided a grating decoder based transmitter in combination with a

15   reconfigurable receiver based on active decoding, for example using delay lines.

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-13-

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